Optical and VLF Imaging of Lightning-Ionosphere Interactions

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LONG-TERM GOALS

This work addresses some of the key topics of space physics research recommended in the National Research Council 2003 report "A Decadal Research Strategy in Solar and Space Physics", namely, the thunderstorm-driven electrodynamic coupling between the troposphere, mesosphere, lower ionosphere, and magnetosphere. Lightning-induced electron precipitation encompasses all of these regions, from atmospheric and mesospheric electrodynamics, to radiation belt scattering, to precipitation and disturbances of ionospheric communication channels. Furthermore, observation of direct lightning-ionospheric coupling mechanisms can lead to the understanding of ion chemical dynamics in the upper-mesosphere, and lower-ionosphere, including determination of ambient electron density profiles and unknown chemical interaction parameters. Sprites and their possible conjugate effects due to relativistic electrons also constitute a coupling between the regions, including lightning effects on the mesosphere and ionosphere. Geomagnetic disturbances highlight the coupling between these regions, with the resulting perturbations in the magnetosphere and ionosphere easily detectable.

OBJECTIVES

Objectives of the current three-year effort are to address the following scientific questions: What role do lightning generated whistlers play in the formation of the slot region of the radiation belts? How can VLF remote sensing be used to quantitatively measure the energy spectra and flux of precipitating electrons associated with LEP events? What is the contribution of MR whistlers and lightning-triggered-plasmaspheric hiss to the loss of electron radiation? How do sprites evolve on a fine spatial and temporal scale, and how does this evolution compare to conventional and streamer breakdown theory? What is the cause of the fine-scale bead-like features of sprites? How does the thundercloud activity relate to the spatial and temporal evolution of sprites? How are sprites and sprite halos related to conductivity perturbations on the ionosphere, observed as early/fast perturbations to VLF transmitter signals? What is the effect of in-cloud lightning on the lower ionosphere? How can VLF remote sensing be used to quantify atmospheric ion-chemistry interaction parameters? Are long-recovering Early VLF events the result of a different causative mechanism than their short-recovery counterparts, and are long recovery events more likely to be observed on all ocean-based paths than paths over land? If so, what is the physical source of this preference?

APPROACH

Our approach consists of the use of optical and wideband VLF/LF measurements to document high altitude optical phenomena and VLF/LF holographic imaging of ionospheric disturbances together with the causative lightning flashes. The VLF/LF antennas are deployed at seven high schools and

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colleges spread across the United States, with the students and teachers at these schools involved in the program as part of our educational outreach efforts. Observations of sprites are also made in the Midwestern United States using high-speed telescopic imaging, photometric measurements, and ELF/VLF measurements of causative sferics. Sprite observations are compared with VLF narrowband and broadband data to establish correlations between sprite features and lightning and ionosphere activity. The key individuals involved are graduate students that are either fully funded under this program or partly funded by an associated NSF grant, ~10% effort of an engineer, and the Principal Investigator. The students are involved in all aspects of the program, including design and construction of equipment and software, deployment, data acquisition and interpretation, as well as educational outreach (for example by providing lectures at the high schools). The engineer is mainly involved in data archiving and increasing data accessibility.

WORK COMPLETED

During the last year, a new version of the data acquisition software was installed at each of the Holographic Array for Ionospheric Lightning (HAIL) sites, and the coverage periods of each site were staggered to provide 24-hours of coverage. Measurements at the sites are ongoing. A paper published in Geophysical Research Letters reported the existence of a previously unrecognized variation of Early VLF events, and because of the extended coverage range of the new HAIL array, the paper was further able to explore the geographic dependencies of these events. A paper published in the Proceedings of the 13th annual International Conference on Atmospheric Electricity (ICAE) presented the existence of daytime ionospheric perturbations intense enough to affect subionospherically propagating VLF signals, and chemical modeling proved effective in predicting the recovery of such events.

In the past year the PIPER (Photometric Imaging of Precipitation of Electron Radiation) photometer instrument was completed and deployed for the first time in two sprite experiments. This instrument is a set of four 16-channel multianode photomultiplier tubes, designed to create high-speed, high-sensitivity 2-dimensional images in two wavelength bands. An algorithm was developed to take the two 16-channel datasets and recombine them into a realistic image. This algorithm is currently being applied to sprite images recorded in 2007.

In July, a first PIPER instrument was deployed at Pic du Midi in the French Pyrenees, in collaboration with the European CAL (Coupling of Atmospheric Layers) research network. This system is remotely operated from Stanford, including power on and off, pointing, and data acquisition. The campaign is ongoing as of October 2007.

Another experiment was conducted in the past summer, following on the experiments of 2004 and 2005, to image sprites at unprecedented spatial and temporal resolution using a high-speed CCD imager mounted on a Dobsonian telescope. While the earlier experiments used cameras of only 1000 or 2000 frames-per-second (fps) and weaker sensitivity, this experiment used an intensified camera capable of up to 10,000 fps at better resolution and higher sensitivity. Furthermore, this experiment saw the deployment of a second PIPER photometer instrument for sprite observations. Results of this experiment are still under analysis.

RESULTS

The following scientific results were obtained and reported in the indicated papers:

Cotts and Inan [2007a] documented the first observation of exceptionally short (>1 second, rapid initial) and very long (~20 minutes, long enduring) recovery components in some Early VLF events. The research showed that long recovery VLF events are 2.5 to 5 times more likely to be observed on oceanic paths, consistent with the oceanic storms where gigantic blue jets have predominantly been observed. The very short time scale has been linked to the rapid attachment of electrons following transient ionization, while the very long recovery is due to the time scales of mutual-neutralization of heavy stratospheric ions.

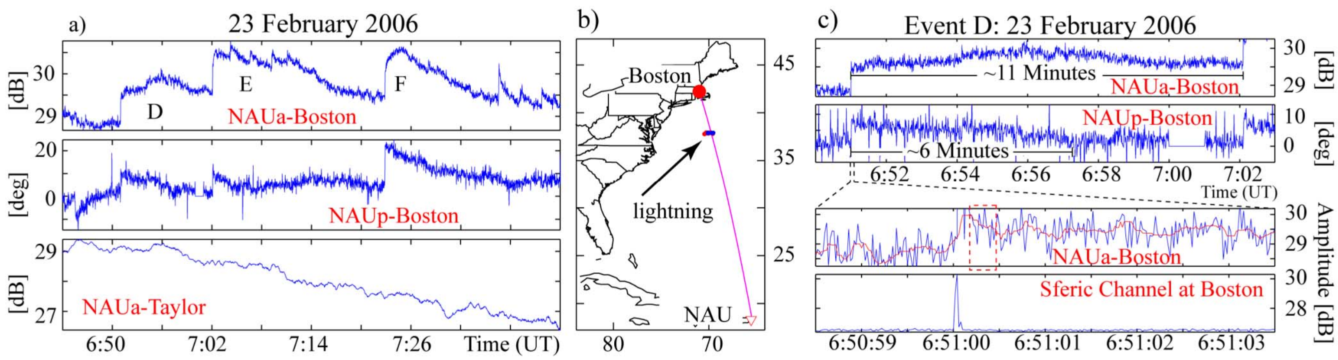

Figure 1: From Cotts and Inan, [2007]. a) Overview of three identified long recovery events, exhibiting three separate types of long recovery: step-events (event D), long amplitude/short phase recovery (event E), long amplitude/long phase recovery (event F). b) Probable location of causative lightning for events. c) Event D, showing onset of event, and rapid initial partial recovery (highlighted by dashed-red box)

Completion of an ion-chemistry model of the upper mesosphere/lower ionosphere [*Inan et al*., 2006; *Lehtinen and Inan*, 2007] has enabled research into the temporal evolution of transient ionization in the earth-ionosphere waveguide (Both LEP and Early VLF events). In agreement with previous results [e.g., *Pasko and Inan* 1994; *Inan et al*., 1988], the model predicts relaxation time scales which span several orders of magnitude, and are dependent on the altitude range in which the transient ionization is located. These results were published in *Cotts and Inan* [2007b] in which it was shown that the calculated recovery time of broadly-distributed (in altitude) transient ionization in the daytime lower-ionosphere/upper-mesosphere matches well with the identified event. Further study of the relaxation of these events will yield information about not only the ambient conditions under which these events take place, but also give an insight into the chemical dynamics at altitude ranges where little is known.

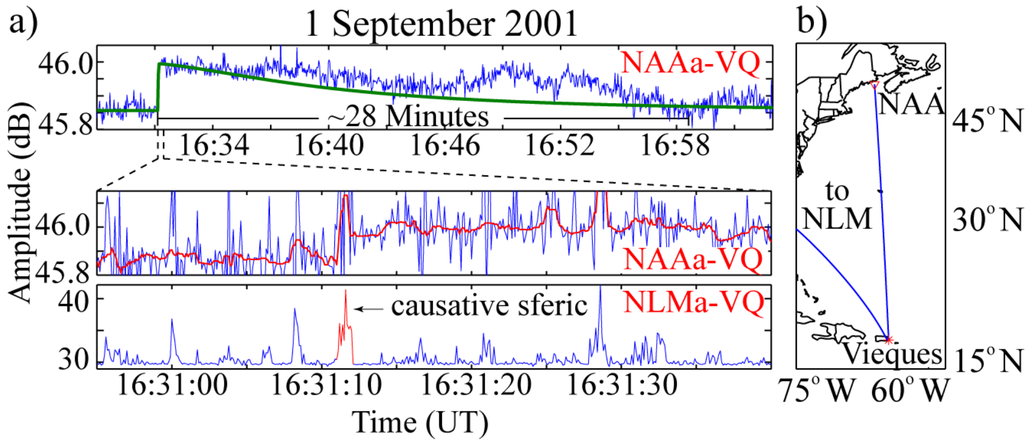

Figure 2: From Cotts and Inan, [2007b]. a) Top panel: Full extent of daytime event, including modeled recovery in green line. Middle panel: Onset of event including 12-point median filtered data in overlaid red line. Bottom panel: Causative sferic. b) Map showing GCP's.

Marshall and Inan [2007b] used archived broadband VLF data from Yucca Ridge, Colorado, from 1995 – 2000, to study correlations between sprites and so-called "sferic bursts", clusters of VLF radiation from lightning. In this study it was shown that sferic bursts originate in in-cloud lightning, specifically the horizontal in-cloud component of large +CG lightning. This paper showed that sprites are often, but not uniquely, correlated with sferic bursts, suggesting that the physical mechanisms involved differ. This result, combined with the results of *Marshall et al* [2006b], which showed a strong – but not one-to-one – correlation between sprites and Early/fast events, has led to a new mechanism, as described below in *Marshall and Inan* [2007c].

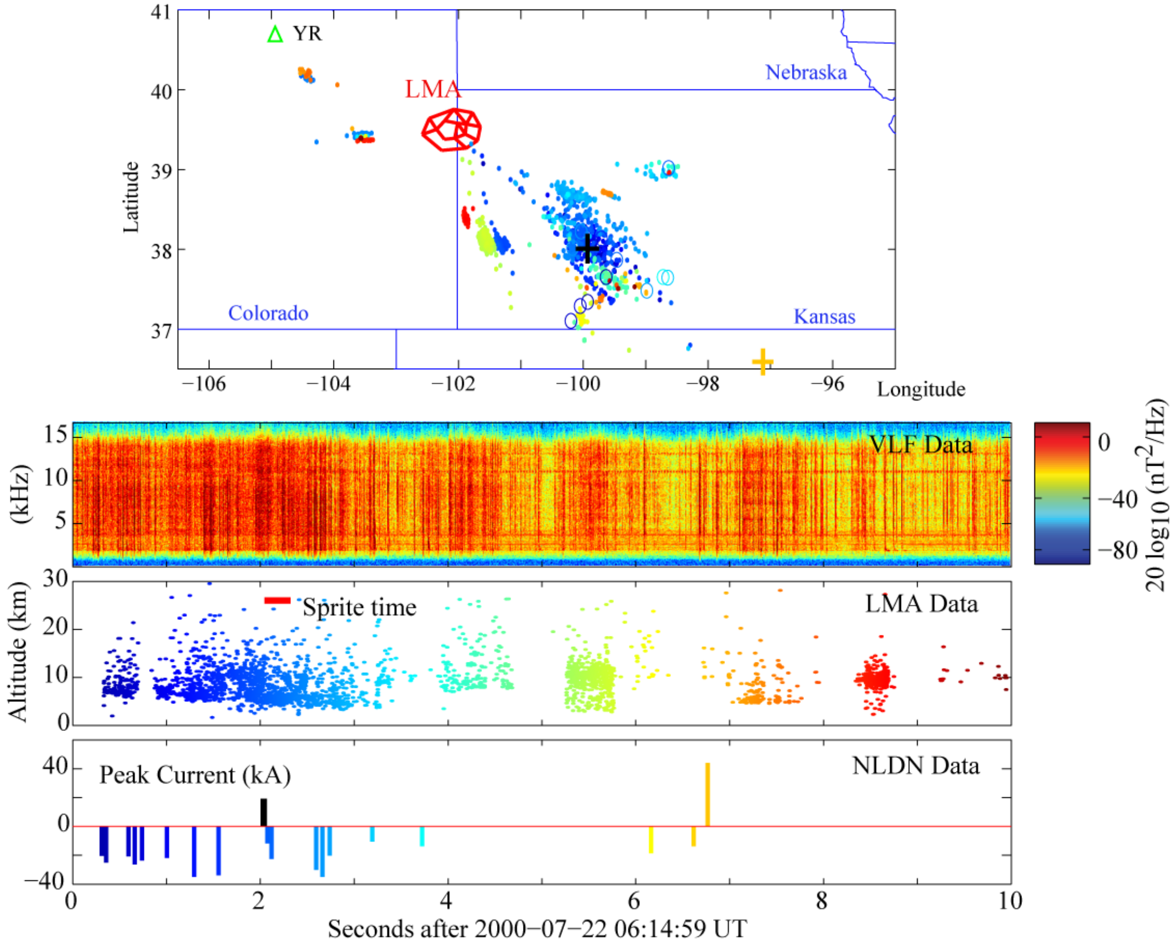

Figure 3: From Marshall et al [2007a]. 10 seconds of VLF broadband data (center), along with Lightning Mapping Array (LMA) and NLDN data. This example shows the strong correlation between the burst activity and the LMA activity, with a sprite occurring in the midst of this activity. The 2D locations of LMA (dots) and NLDN (circles) data are shown on the map.

Marshall and Inan [2007a] showed that in many cases, sprites are followed by luminuous discharges which appear to connect the base of the preceding sprite to the cloudtop. This connection has implications for the flow of current between the cloud and the ionosphere above, through a two-step discharge process. These "secondary TLEs" seem to follow only the largest sprites, and are explained by the *Greifinger and Greifinger* [1976] model of a moving capacitor plate. This study also reported on one case of a secondary TLE caught in the 1000 fps telescopic field-of-view, and showed its propagation to be much slower, and its lifetime to be much longer, than all observed sprites.

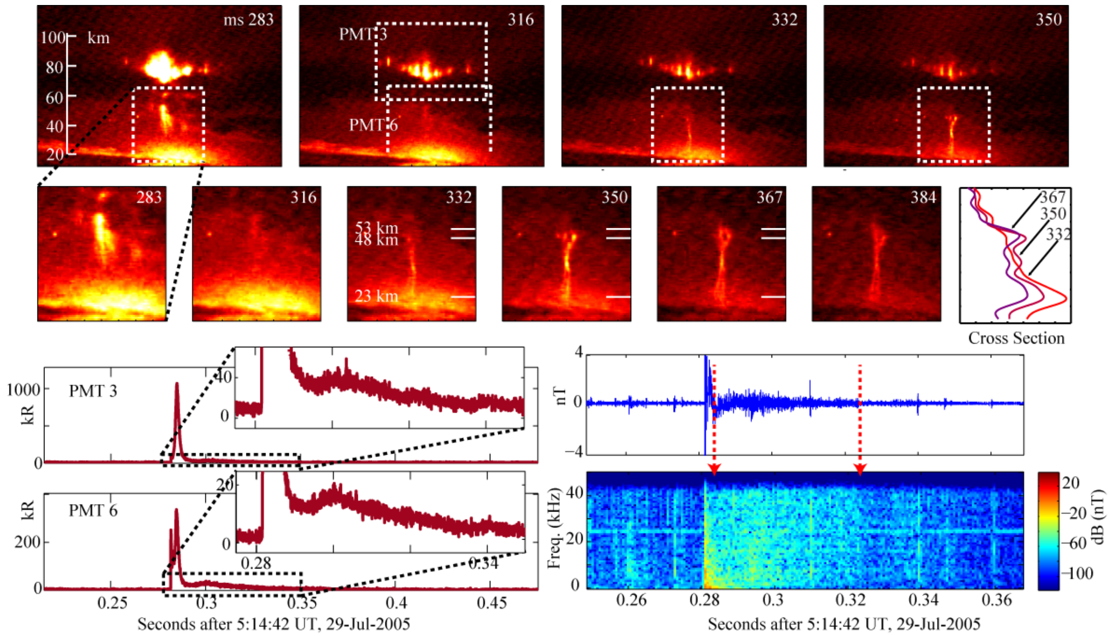

Figure 4: From Marshall et al [2007b]. Example of a secondary TLE event. One frame (16 ms) after the sprite, a discharge appears between the cloud and the lower extent of the sprite. This may provide an electrical connection between the ionosphere and the thundercloud. The event coincides with the VLF sferic burst (below right), which is explained in the previous section.

Marshall and Inan [in preparation] demonstrates that many Early/fast events are actually caused by the lightning electromagnetic pulse (EMP), rather than the quasi-electrostatic (QE) heating as is generally believed. In particular, this paper shows that the EMP associated with the in-cloud component of positive cloud-to-ground (+CG) lightning has sufficient fields to cause dissociative attachment to molecular oxygen, reducing the electron density at 70-85 km altitude enough to perturb subionospheric VLF signals. This explanation agrees with data and is able to explain for the first time the one-to-one association between Early/fast events and sferic bursts.

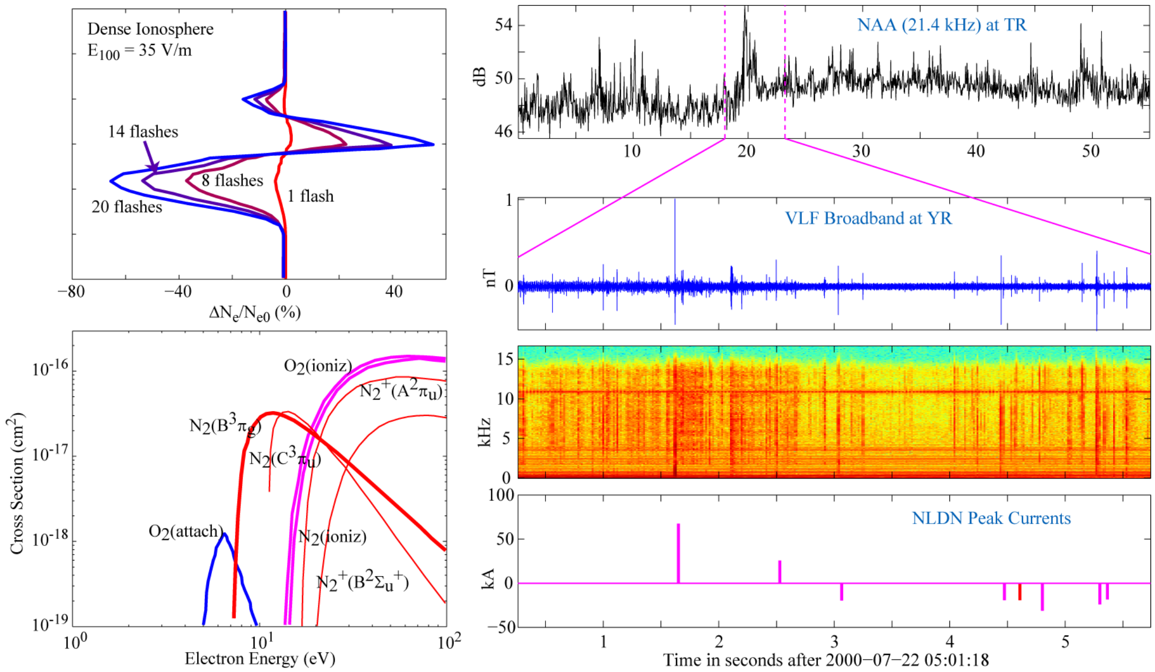

Figure 5: Top left: a 35 V/m EMP from lightning causes some ionization, but much more attachment at lower altitudes, evidenced by a reduction in electron density. This is due to the fact that attachment has a lower electron energy threshold compared to ionization or even optical excitation (lower left). At right: an example of an Early/fast event correlated with a strong sferic burst and a sprite, from 2000 VLF data at Yucca Ridge, CO.

IMPACT/APPLICATIONS

The general impact of our results is the quantification of ionospheric variability (especially the mesosphere and the D region) due to both lightning discharges and radiation belt particle precipitation. VLF Holographic measurements with the HAIL system have led to the identification of the underlying structure and temporal and spatial characteristics of ionospheric disturbances associated with lightning discharges. In view of a global lightning rate of ~100 flashes per second, the contribution of lightning discharges may be globally important to both ionospheric variability and the possible role in the formation of the slot region of the radiation belts. Furthermore, our correlative studies of sprites, early/fast perturbations and associated VLF activity result in quantification of the effect of sprites on the ionosphere.

TRANSITIONS

The establishment of a user-friendly web-based data viewer program (http://hailweb.stanford.edu/vlfdataviewer.html) updated daily, which allows remote access to all HAIL data and expands both our educational outreach component and facilitates our future collaborations with other researchers in the field. High school students can view 1-s resolution VLF amplitude or phase data, recorded at their host school or at any other HAIL site, and explore ionospheric effects of recent events such as solar storms, galactic gamma ray bursts, and local thunderstorms. The various MATLAB-based analysis software developed by Stanford for the HAIL research project are being used by interested high school students at the schools that house our equipment, as well as by collaborating researchers from other institutions [e.g., *Haldoupis et al.,* 2004, 2006; *Mika et al.,* 2005, 2006].

RELATED PROJECTS

The Atmospheric Sciences Division of NSF jointly funds the holographic VLF/LF measurements component of our project. Other related projects include VLF/LF observations carried out at Palmer Station, Antarctica; University of Iraklio, Crete; Firat University, Turkey; and the Centre National de la Recherche Scientifique (CNRS) in Nancay, France, which allow us to examine characteristics of these events in settings other than over the United States.

PUBLICATIONS

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